Research Article

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Effect of fiber breakage position on the mechanical performance of unidirectional carbon fiber/epoxy composites

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Abstract: Fiber breakage is one of the most negative factors that affect the mechanical performance of unidirectional carbon-fiber (CF)-reinforced composites. In the present study, unidirectional CF-reinforced epoxy (CF/epoxy) laminates with and without fiber breakages located in different layers were manufactured from prepreg via hot compression. The static and cyclic flexural mechanical properties of the unidirectional CF/epoxy laminates were determined through static and low-cycle three-point bending tests. Flexural behavior was observed by using optical microscopy to discuss the failure behavior of the unidirectional CF/epoxy laminates. Results indicated that fiber breakages in different layers led to the static and cyclic mechanical degradation of the unidirectional CF/epoxy laminates. Moreover, fiber breakages in the tension side displayed higher flexural strength and better cyclic performance than those in the compression side.

Keywords: CF, polymer matrix composites, fiber breakage, mechanical properties

1 Introduction

Carbon-fiber (CF)-reinforced composites (CFRPs) are widely used in various applications because of their excellent properties, such as light weight [1,2], crashworthiness [3–6], high specific strength [7,8], impact resistance [9,10], excellent fatigue resistance [11,12], and corrosion resistance [13,14]. The mechanical properties of composites are related to various parameters, including reinforcement types [15,16], matrix types [17,18], fillers [19–21], fiber orientation [22,23], reinforced structures [24–26], reinforcement surface modification [27,28], interfacial bonding capability [29,30], service environment [31,32], and processing conditions [33,34]. Most of the mechanical properties of matrix composites are well known to be controlled by the stiffness and strength of the reinforcing fibers [35]. Current theories for predicting the mechanical performance (modulus, strength, and toughness) of composites are based on the assumption that the specimens are initially undamaged [36]. As-processed materials are assumed to lack severe defects, such as matrix regions without any supporting fibers or regions wherein the fibers are initially broken [37]. However, avoiding some types of processing damages, such as voids [38], fiber damage or fiber breakage [39], interface damages [40], and residual stress [41], during the manufacturing of composites is difficult. These damages adversely affect composite properties.

The present study aims to investigate the effect of fiber breakage caused by the manufacturing process on the mechanical performance of unidirectional composites. One of the effective ways to investigate the corresponding failure behaviors of unidirectional composites with initial fiber damages is modifying the architecture of the original composites, e.g., by introducing designed ply discontinuities into different layers. Discontinuous ply composites have been used for various purposes as reported in previous references. Czél et al. [42] investigated CF/epoxy prepreg composites with overlapping

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discontinuities at the ply level and found a significantly nonlinear pseudo-ductility response due to progressive interlaminar damage under tensile loading. Taketa et al. [43] proposed a new compression molding approach, namely, unidirectionally arrayed chopped strands (UACS). In this approach, the introduction of designed slits into unidirectional carbon preregs improves the formability of the material for manufacturing components with complex shapes. Li et al. [44] proposed new UACS designs to improve the existing UACS laminates with continuous angled slits by introducing discontinuous angled slits into unidirectional preregs. Malkin et al. [45] utilized cut-ply preregs to create gradual and controlled failure in unidirectional CF/epoxy composites under four-point bending. Perremans et al. [46] studied the effect of discontinuity patterns on the mechanical performance of bamboo–fiber–reinforced epoxy composites. Their results indicated that tensile stiffness is negligibly influenced and that in contrast to the introduction of a unidirectional continuous bamboo–fiber composite, the introduction of randomized fiber end discontinuities leads to the preservation of 85% of the longitudinal tensile strength. Trauth and Weidenmann [47] and Trauth et al. [48] investigated the effect of hybridization on the mechanical properties of continuous–discontinuous sheet molding compounds that combine the advantages of discontinuous chopped-glass-fiber-reinforced composites and unidirectional continuous CFRPs. Hybridization leads to a considerable enhancement in mechanical [47] and puncture [48] properties.

In the present study, unidirectional CF/epoxy laminates were manufactured from prepreg through hot compression. One piece of cut-ply prepreg was laid at different layers of the CF/epoxy laminates. Three-point bending tests and low-cycle bending tests were performed to investigate the effect of fiber breakage location on the flexural and cyclic mechanical performances of the CF/epoxy laminates.

2 Materials and experimental procedures

2.1 Materials and composite manufacturing

Unidirectional CF/epoxy composites were prepared by laying up to 19 layers of CF/epoxy preregs (USN20000; Weihai Guangwei Composites Co., Ltd., China) with a stacking sequence of $[0]_{19}$. One layer of CF/epoxy prepreg was cut into strips with a vertical-to-fiber orientation and a fiber length of 2 cm. One layer of cut prepreg and 18 original preregs were laminated in the set order shown in Figure 1. In detail, the cut prepreg was laminated in the 1st, 4th, 7th, 13th, 16th, and 19th layers. The laminated preregs were transferred to a hot compression machine (Model 3856; Carver, Inc., Wabash, USA) for curing. The detailed molding condition is shown in Figure 2.

2.2 Experimental procedures

2.2.1 Optical observation

CF/epoxy laminates before and after flexural tests were cast in epoxy resin for 24 h at room temperature to preserve the morphology of the selected zones. Then, specific cross-sections of embedded CF/epoxy laminates were selected by using a cutting machine and polished with sandpaper of different meshes. Finally, the cross-sections were photographed with an optical microscope (VHX-500F; Keyence Corporation, Osaka, Japan), which was used to study structures, impregnation conditions, and crack propagation.

Figure 1: Schematic of CF/epoxy laminates with fiber breakage.

Figure 2: Curing condition of the composites.

2.2.2 Three-point bending test

Static flexural tests were carried out through three-point bending tests in accordance with the ASTM D7264 [49] standard. Five specimens of CF/epoxy laminates with and without fiber breakage at different layers were measured. The flexural mechanical properties of the aforementioned CF/epoxy laminates with the geometry of $80\text{ mm} \times 10\text{ mm} \times 2\text{ mm}$ were determined by using a universal testing machine (Instron 5696; Instron, Canton, MA, USA) equipped with a 5 kN load cell at a span length of 64 mm and a rate of 5 mm min^{-1} .

2.2.3 Cyclic bending tests

The same Instron universal testing machine was applied to perform the cyclic bending test on the unidirectional

CF/epoxy composites under load control with a sinusoidal waveform. The maximum cyclic load was set as 95, 92.5, and 90% of the maximum flexural load of each specimen. The flexural load–displacement curves and flexural modulus of the cyclic test were recorded and calculated automatically by Bluehill 3 software (Instron).

3 Results and discussion

3.1 Cross-section of unidirectional CF/epoxy laminates

The cross-section observations of CF/epoxy laminates with and without fiber breakage in different layers are shown in Figure 3(a)–(g). A unidirectional CF/epoxy laminate in good impregnation condition and without any fiber breakages is depicted in Figure 3(a). The unidirectional CF/epoxy laminates with fiber breakages in the 1st, 4th, 7th, 13th, 16th, and 19th layers are presented in Figure 3(b)–(g). The fiber breakages, which were marked with yellow arrows, could be observed in the predesigned layer clearly. Meanwhile, all the unidirectional CF/epoxy laminates were in good fiber impregnation condition.

3.2 Flexural mechanical properties of unidirectional CF/epoxy laminates

The typical flexural stress–strain curves of the unidirectional CF/epoxy laminates with and without fiber

Figure 3: Cross-sections of CF/epoxy laminates with fiber breakage in different layers: (a) original, (b) first layer, (c) fourth layer, (d) seventh layer, (e) 13th layer, (f) 16th layer, and (g) 19th layer.

breakages in different layers are given in Figure 4(a)–(f). The unidirectional CF/epoxy laminates without fiber breakage exhibited a linear relationship between flexural stress and stress throughout the whole flexural process. The stress of the original CF/epoxy laminates dropped dramatically upon reaching the maximum value. This behavior indicated typical brittle fracture behavior. The stress–strain curves of the CF/epoxy laminates with fiber breakages

located in the first layer (CF/epoxy-1st) are marked in red in Figure 4(a). The flexural stress obviously increased linearly before the first degradation stage, indicating that no severe damage occurred in the CF/epoxy-1st laminates before the flexural strain approached 0.008. Subsequently, the flexural stress gradually decreased irregularly, indicating that damage continuously occurred with the increase in the flexural strain. Similar results could be observed in

Figure 4: Typical flexural stress–strain curves of CF/epoxy laminates with fiber breakages in different layers: (a) first layer, (b) fourth layer, (c) seventh layer, (d) 13th layer, (e) 16th layer, and (f) 19th layer.

CF/epoxy laminates with fiber breakage in the 4th, 7th, 13th, and 16th layers as illustrated in Figure 4(b)–(e). However, the flexural stress–strain curves of the CF/epoxy-19th laminates were nonlinear, indicating that some damages or cracks had already gradually occurred before stress degradation.

Flexural mechanical properties, including flexural modulus and flexural strength, and their coefficients of variation are summarized in detail in Table 1. The flexural modulus and strength of the CF/epoxy laminates with and without fiber breakage in different layers are provided in detail in Figure 5. The modulus and strength of the CF/epoxy laminates with fiber breakage in various layers had clearly decreased by 2.9–7.5% and 6.8–24.9% of the original values. In particular, the flexural strength of the CF/epoxy laminates with fiber breakage in the compression side was lower than that of the laminates with fiber breakage in the tension side. The lower compression property than tensile property of the unidirectional CFRPs led to the initiation of damage from the upper side [50]. Therefore, the degradation of compression-side properties weakened the flexural strength of the CF/epoxy laminates to a great extent. The ultimate strain of the CF/epoxy laminates with fiber breakage in the compression side (first, fourth, and seventh layers) ranged from 0.7 to 0.8% and was lower than that of the laminates with fiber breakage in the tension sides (13th, 16th, and 19th layers) as presented in Figure 4.

3.3 Relationship between flexural modulus and strength of CF/epoxy laminates

The relationship between the flexural modulus and strength of the CF/epoxy laminates with fiber breakage in different layers is shown in Figure 6. As mentioned above, the flexural modulus and strength of the CF/epoxy laminates with fiber breakage decreased relative to those of the original

Figure 5: Flexural modulus and strength of CF/epoxy laminates with and without fiber breakage in different layers.

CF/epoxy laminates without fiber breakage. The CF/epoxy laminates with fiber breakage in the upper compression side (first, fourth, and seventh layers) exhibited similar modulus but lower flexural strength than the laminates with fiber breakage in the lower tension side (13th, 16th, and 19th layers) as explained above. Interestingly, an obvious negative linear relationship between flexural modulus and strength was observed in CF/epoxy laminates with fiber breakage in the compression side, whereas a positive linear relationship was observed in the laminates with fiber breakage in the tension side as depicted in Figure 6. In other words, fibers with high modulus in the tensile side and fibers with low modulus in the compression side contributed to the enhancement in the flexural mechanical properties of CF/epoxy laminates. As depicted in Figure 4(a)–(c), the strain corresponding to the first stress degradation of the CF/epoxy laminates with fiber breakage in the compression side was limited (<1.0%). Therefore, the low modulus of the CF/epoxy laminates prolonged the deformation time needed to reach the threshold of severe damage and finally resulted in high flexural properties. As illustrated in Figure 4(d)–(f), the ultimate strain of the CF/epoxy laminates with fiber breakage in the tension

Table 1: Flexural mechanical properties of CF/epoxy laminates

Type	Flexural modulus (GPa)	C.V. (%)	Flexural strength (MPa)	C.V. (%)
Original	162.96	0.89	1693.59	3.94
CF/epoxy-1st	152.75	1.22	1339.96	4.38
CF/epoxy-4th	158.19	1.92	1271.98	5.42
CF/epoxy-7th	150.75	1.83	1453.23	4.01
CF/epoxy-13th	152.26	4.14	1514.10	5.54
CF/epoxy-16th	154.93	1.37	1577.89	2.12
CF/epoxy-19th	150.66	2.57	1461.19	4.54

Figure 6: Relationship between flexural modulus and strength of CF/epoxy laminates with fiber breakage in different layers.

side was high ($>1.0\%$), and no stress degradation occurred before the strength was reached. Therefore, the high modulus of the CF/epoxy laminates was conducive to the enhancement of flexural properties.

3.4 Optical observation on the static fracture behavior of CF/epoxy laminates

Cross-section observations on the flexural fracture behavior of the CF/epoxy laminates with fiber breakage in different layers after static bending tests are shown in Figure 7. As illustrated in Figure 7(a), the original CF/epoxy laminates separated into two parts after flexural tests. This behavior indicated brittle fracture mode. The failure process was transient, and the stress decreased dramatically upon reaching the maximum value as shown by the black dotted lines in Figure 4. By contrast, the CF/epoxy laminates with fiber breakage in the compression side exhibited fiber buckling, fiber breakage, and delamination in the compression side but no obvious damages in the tension side as shown in Figure 7(b)–(d). Therefore, local buckling or kinking damages initiated from the upper side once the flexural strain reached $0.7\text{--}0.8\%$. Then, additional fibers were damaged, and cracks propagated along the fibers, leading to stress degradation as shown in Figure 4(a)–(c). As presented in Figure 7(e) and (f), the CF/epoxy laminates with fiber breakage in the tension side exhibited obvious longitudinal cracks along the fibers in the lower side. The fracture behaviors of the CF/epoxy-13th and CF/epoxy-16th laminates were similar to those of the CF/epoxy laminates

with fiber breakage in the compression side. However, the longitudinal cracks in CF/epoxy-13th and CF/epoxy-16th propagated along the fiber direction over a relatively long distance near the lower tension side. Notably, the initial damage of CF/epoxy-19th laminates occurred from precut fiber breakage owing to stress concentration and then propagated between layers, accounting for the nonlinear flexural stress–strain curves presented in Figure 4(f).

3.5 Low-cycle tests on unidirectional CF/epoxy laminates

The typical cyclic flexural stress–strain curves of the CF/epoxy laminates with fiber breakages in different layers at cyclic stress ratios of 95, 92.5, and 90% are shown in Figure 8(a-1)–(f-1), (a-2)–(f-2), and (a-3)–(f-3), respectively. The relationships between residual modulus ratio and cycles to failure of the CF/epoxy laminates with and without fiber breakage in different layers are shown in Figure 9. As illustrated in Figure 8(a), the cycles to failure of the original CF/epoxy laminates at 95, 92.5, and 90% stress ratios were 4, 10, and 24, respectively. The residual modulus of cycled CF/epoxy laminates remained at a stable level and then suddenly decreased 20–30% in the last cyclic bending test as indicated in Figure 9(a). Meanwhile, the ultimate flexural strains of the cycled CF/epoxy laminates were higher than those of the original ones. Subjecting the original unidirectional CF/epoxy laminates through several cycles of flexural loading caused the local buckling and kinking of CFs at the upper layers that led to modulus degradation. As illustrated in Figure 8(b) and (g) and similar to those shown in Figure 8(a), the cycles to failure of the CF/epoxy-1st and CF/epoxy-19th laminates increased with the decrease in normalized maximum stress. However, the modulus of both laminates underwent a continuous degradation process. The modulus first decreased significantly then steadily decreased to the last cycle as depicted in Figure 9(b) and (g). High cyclic flexural stress obviously contributed to the low residual modulus of the CF/epoxy-1st and CF/epoxy-19th composites. This effect was closely related to damage. The modulus of the CF/epoxy-1st composites decreased significantly because some fiber buckling and kinking occurred in the compression side, whereas the modulus of the CF/epoxy-19th composites decreased gradually and remained at a relatively high level ($>90\%$) owing to crack initiation from the tip of fiber breakage, crack propagation along the fiber layer, and sparse fiber breakage

Figure 7: Cross-section observations on the flexural fracture behavior of CF/epoxy laminates with fiber breakage in different layers after bending tests: (a) original, (b) first layer, (c) fourth layer, (d) seventh layer, (e) 13th layer, (f) 16th layer, and (g) 19th layer.

in the tension side. As shown in Figure 8(c), the cycles to failure of the CF/epoxy-4th laminates at 95 and 92.5% stress ratios were 9 and 22, respectively. However, the CF/epoxy-4th laminates at 90% stress ratio did not fracture after 100 cycles. As presented in Figure 9(c), the modulus of the CF/epoxy-4th laminates under 95% stress ratio cyclic tests decreased to 57% after ten cycles because the same obvious damage occurred in the first cycle as shown in Figure 8(c-1). As depicted in Figure 8(d), the CF/epoxy-7th laminates experienced failure after 42 cycles at 95% stress ratio. However, the CF/epoxy-7th laminates at 92.5 and 90% stress ratios did not fracture during 100 cycles. During the cyclic tests, the modulus of the CF/epoxy-7th laminates remained at a stable level as shown in Figure 9(d). The cycles to failure of the CF/epoxy-13th laminates at 95, 92.5, and 90% stress ratios were 2, 10, and 77 as presented in Figure 8(e-1)–(e-3), respectively. Meanwhile, the cycles to failure of the CF/epoxy-16th laminates at 95 and 92.5% stress ratios were 2 and 9 as depicted in Figure 8(f-1) and (f-2), respectively. Above all, the modulus of the CF/epoxy laminates with fiber breakages in the tension side (13th, 16th, and 19th layers) clearly remained at a high level (over 80%). However, the modulus of the original CF/epoxy laminates and laminates with fiber breakages in the compression side (first, fourth, and seventh layers) decreased to a very low level (50 to 80%) after cyclic bending tests. The flexural modulus of the unidirectional laminates was mainly dependent on their qualities and was particularly dependent on damage form and extent. The change in modulus indirectly reflected the damage condition of the unidirectional laminates. The better tensile properties than compression properties of the unidirectional CF/epoxy laminates lead to the initial occurrence of buckling

failure in the compression side. The compression side of the CF/epoxy laminates was weaker than the tension side. Therefore, cyclic flexural loading had more negative effects on the upper compression side than on the other side.

The relationship between cycles to failure and normalized maximum stress (equal to maximum cyclic stress over flexural strength) of all the CF/epoxy laminates is shown in Figure 10. The cycles to failure clearly increased with the decrement in normalized maximum stress. The laminates with fiber breakages in the compression/upper side (first, fourth, and seventh layers) exhibited better cyclic performance than the original CF/epoxy laminates, and the opposite behavior was observed for the laminates with fiber breakages in the tension/lower side (13th, 16th, and 19th).

3.6 Fracture behavior of CF/epoxy laminates in cyclic bending tests

The cross-section observation on the flexural fracture behavior of CF/epoxy laminates with fiber breakage in different layers after cyclic bending tests at 95% normalized maximum stress ratio is shown in Figure 11. As presented in Figure 11(a), the CF/epoxy laminates did not separate into two parts after the cyclic bending tests. However, the fracture initiated from the upper side to the lower side with longitudinal delamination along the fiber orientation. The CF/epoxy-1st, CF/epoxy-4th, and CF/epoxy-7th laminates demonstrated similar behaviors as shown in Figure 11(b)–(d), respectively. The delamination of all the aforementioned laminates (original, first,

Figure 8: Typical cyclic flexural stress–strain curves of CF/epoxy laminates with and without fiber breakage in different layers: (a) original, (b) 1st layer, (c) 4th layer, (d) 7th layer, (e) 13th layer, (f) 16th layer, and (g) 19th layer.

Figure 9: Relationship between residual modulus ratio and cycles to failure of CF/epoxy laminates with and without fiber breakage in different layers: (a) original, (b) 1st layer, (c) 4th layer, (d) 7th layer, (e) 13th layer, (f) 16th layer, and (g) 19th layer.

fourth, and seventh) was located between the 13th and 16th layers. As shown in Figure 11(e)–(g), local fiber buckling could be observed in the compression side of the CF/epoxy-13th, CF/epoxy-16th, and CF/epoxy-19th

Figure 10: Normalized maximum stress versus cycles to failure of the CF/epoxy laminates with and without fiber breakages in different layers: (a) 1st layer, (b) 4th layer, (c) 7th layer, (d) 13th layer, (e) 16th layer, and (f) 19th layer.

laminates. Interestingly, delamination could be observed in the corresponding precut layers of the composites after cyclic bending tests.

4 Conclusion

A layer of unidirectional CF/epoxy prepreg was cut with a fixed length and laminated into non-cut prepreps at different layers. The laminated CF/epoxy preforms were cured

under heating and compression via hot compression. The static and cyclic flexural mechanical performances of the unidirectional CF/epoxy laminates were tested by using static and cyclic three-point bending tests. Failure behavior was observed through optical microscopy. The obtained results could be summarized as follows:

- (a) Fiber breakages in the different layers of the unidirectional CF/epoxy laminates led to flexural modulus and strength degradation. Compression properties were lower than tensile properties, resulting in damage

Figure 11: Cross-section observation on the flexural fracture behavior of CF/epoxy laminates with fiber breakage in different layers after 95% stress cyclic bending tests: (a) original, (b) 1st layer, (c) 4th layer, (d) 7th layer, (e) 13th layer, (f) 16th layer, and (g) 19th layer.

initiation from the upper side. Therefore, fiber breakage in the upper layers exhibited similar modulus but lower flexural strength than that in the lower layers.

- (b) High modulus in the tension side and low modulus in the compression side were beneficial for increasing the strength of CF/epoxy laminates. The low modulus of the CF/epoxy laminates with fiber breakage in the tension side prolonged the time to deformation required to reach the threshold of severe damage and finally enhanced flexural properties. The ultimate strain of the CF/epoxy laminates with fiber breakage in the tension side was high, and stress degradation did not occur before strength was reached. Therefore, the high modulus of the CF/epoxy laminates with fiber breakage in the tension side was conducive for improving flexural properties.
- (c) At a high normalized maximum stress ratio, laminates with fiber breakages in the upper side exhibited better cyclic performance than the original CF/epoxy laminates, whereas the laminates with fiber breakages on the lower side did not because of their different failure behaviors.

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